Energy Policy 114 (2018) 355–366

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Trade-offs and synergies between universal electricity access and climate change mitigation in Sub-Saharan Africa

Anteneh G. Dagnachew[a,*], Paul L. Lucas[a], Andries F. Hof[a,b], Detlef P. van Vuuren[a,b]

[a] PBL Netherlands Environmental Assessment Agency, The Hague, Netherlands
[b] Copernicus Institute of Sustainable Development, Utrecht University, Netherlands

ARTICLE INFO

Keywords:
Electricity access
Climate change mitigation
Sub-Saharan Africa

ABSTRACT

Access to electricity services is fundamental to development, as it enables improvements to the quality of human life. At the same time, increasing electricity access can have notable consequences for global climate change. This paper analyses trade-offs and synergies between achieving universal electricity access and climate change mitigation in Sub-Saharan Africa, using the IMAGE-TIMER integrated assessment model. For this purpose, we analysed developments in a number of indicators that describe demand, production, and costs of the future power system under various scenarios with and without climate change mitigation policies. The results show that, achieving universal electricity access requires an annual investment of USD 27–33 billion until 2030 on top of baseline investment. There is a strong synergy in emissions reduction and investment savings, particularly driven by the regions' efficiency improvements of household appliances (the purchase of efficient appliances and the efficient use of the appliances). On the other hand, climate mitigation policies are projected to increase the cost of electricity per kWh, depending on fossil fuel share in the mix. Therefore, we conclude that, climate policies will need to be combined with complementary policies- e.g. pro-poor tariffs, fuel subsidies, and cross subsidization- to protect the poor from increasing electricity prices.

1. Introduction

Ensuring access to affordable, reliable, sustainable and modern energy for all is one of the Sustainable Development Goals (SDG7) (Un, 2015) and is also acknowledged by the Paris Agreement as an important need (Unfccc, 2015). The key rational behind the emphasis on energy access is that access to modern energy services is fundamental to development (Hollberg, 2015). Access to electricity, for instance, allows the use of appliances like mobile phones, radios and fans, while lighting provides extra hours to study or work. Still, over 1.2 billion people did not have access to electricity in 2013; more than half of which live in Sub-Saharan Africa (IEA, 2014). Achieving SDG7 thus requires Sub-Saharan African countries to expand electricity access substantially, especially since population is projected to grow rapidly. However, the goal of increasing electricity access is coupled to other SDGs and societal goals, including mitigation of climate change (Van Vuuren et al., 2012). This is also explicitly recognized by SDG7, which, next to universal access to modern energy sources, also includes targets on renewable energy and energy efficiency.

There are a number of possible trade-offs between providing access to electricity and climate policy. One such trade-off is that increasing electricity access could contribute to greenhouse gas emissions, both directly by increasing energy consumption, and indirectly by promoting economic growth (IRENA, 2015). Several studies have shown that the direct impact of providing electricity access is relatively small: These studies typically find an increase in emissions of around 2–4% (See for instance Van Vuuren et al., 2012 and Un-Ohrlls, 2014 for studies at the global scale, Pachauri, 2014 for India, and Sanchez and Tozicka, 2013 on South Africa). The reason is that additional energy consumed by poor households is expected to be very small compared to the average consumption, while the newly gained access contributes significantly to human development. The indirect impact from promotion of economic growth is more uncertain and more difficult to assess, and will most likely be a long-term effect. Another possible trade-off is that policies aimed at climate change mitigation can negatively impact energy access by increasing energy prices. For instance, several studies have shown that mitigation policies could slow down the switch from traditional biomass to modern fuels for cooking and heating (Cameron et al., 2016; Daioglou et al., 2012; Lucas et al., 2013).

To the best of our knowledge, there are no studies in literature that specifically explore the relationships between climate mitigation policies and electricity access in Sub-Saharan Africa. This study addresses

* Corresponding author.
E-mail address: Anteneh.dagnachew@pbl.nl (A.G. Dagnachew).

https://doi.org/10.1016/j.enpol.2017.12.023
Received 2 June 2017; Received in revised form 13 November 2017; Accepted 17 December 2017
Available online 22 December 2017
0301-4215/ © 2017 Elsevier Ltd. All rights reserved.

these omissions by analysing the impact of mitigation policies on electricity access in Sub-Saharan Africa, as well as the impact that achieving universal electricity access in Sub-Saharan Africa has on global climate change. Furthermore, most existing studies on electricity access in Sub-Saharan Africa (Deichmann et al., 2010; Bazilian et al., 2012; OECD/IEA, 2015) assume a fixed minimum level of electricity consumption for all households, neglecting the dynamic process where electricity consumption increases with growing wealth. In this study, we assess the impact of different electricity consumption levels for urban and rural households and various income layers. As such, the main research question of this article is:

1.1. What are key synergies and trade-offs between improving electricity access and climate mitigation in Sub-Saharan Africa?

As a continuation of our previous work (Dagnachew et al., 2017), which addresses the effect of various levels of electricity consumption on installed capacity and investment, this paper presents the interaction between universal electricity access and climate change mitigation efforts. We focus on a number of indicators that describe demand, production, and costs of future developments in the power system in Sub-Saharan Africa under several scenarios. The scenarios differ with regard to electricity access targets and implementation of climate mitigation policy. We have used the Integrated Assessment Model (IAM) IMAGE-TIMER (Van Vuuren et al., 2014), including the electrification model described in Dagnachew et al. (2017) and the household electricity demand model described in Daioglou et al. (2012). This model is particularly suited to the analysis, as it combines a detailed electrification model containing several on-grid and off-grid electrification options, with an IAM that takes into account the synergies and trade-offs with (global) climate mitigation policies. The choice between electrification systems (grid, mini-grid and stand-alone) is based on local data about socio-economic characteristics, and potentials and prices of various off-grid technologies (solar PV, wind power, mini-hydro, diesel generators).

The structure of the rest of the paper is as follows: Section 2 presents the methodology employed in this paper, where the model and the scenarios are described; Section 3 presents the results using the indicators listed above; Section 4 presents a brief discussion on the model performance and results and uncertainties, and Section 5 provides conclusions on policy implications and suggestions for further research.

2. Methodology

2.1. The IMAGE-TIMER model

The IMAGE model is an integrated assessment model looking at future global environmental change (Stehfest et al., 2014). It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity loss and human well-being. In this paper, we use the energy-system simulation model (TIMER), a sub-model of the IMAGE framework (Van Vuuren et al., 2006, 2016). We focus on household electrification, using the electrification sub-model described in Dagnachew et al. (2017) and the household electricity demand sub-model described in Daioglou et al. (2012).

TIMER describes the demand and supply of 12 different energy carriers for 26 world regions. In the model, Sub-Saharan Africa is divided into four regions: ‘western & central Africa’, ‘eastern Africa’, ‘Republic of South Africa’, and ‘the rest of southern Africa’ (see Fig. i in the Supplementary text). Key issues that TIMER addresses are transitions to more sustainable energy supplies; exploitation of energy resources to meet future demand; and the potential role of the energy conversion sector and individual technologies, particularly in power production, in achieving a more sustainable energy system. In choosing energy supply carriers, TIMER uses a multi-logit approach that selects predominantly the cheapest energy technologies, but assigns a market share to technologies that have somewhat higher costs as well, taking into account heterogeneous local characteristics where relevant. In some exceptions, optimization algorithms are used for simplification. In order to represent climate policy in the model, a ‘carbon price’ is introduced to induce a shift towards low-carbon technologies. Key mitigation options include increasing the share of nuclear power and renewables, equipping fossil-fuel technologies with Carbon Capture and Sequestration (CCS), improving energy efficiency, and reducing non-CO_2 greenhouse gas emissions. More detail on the assumptions and parameters of the TIMER model can be found in Van Vuuren et al. (2006).

Household electricity demand is determined for five income classes, for both rural and urban households, based on the demand for different energy services. The household demand model projects the electricity demand by looking at the specific end-use function (i.e. cooking, appliances, and lighting) and their drivers (population, floor space, appliance ownership, appliance efficiency, weather, and electricity price) and relating these functions to economic development. Empirical data shows that household electricity consumption correlates positively with income, which is used in the model, taking into account appliance ownership (Daioglou et al., 2012). Next to income, total household electricity consumption is determined by appliance efficiency. Change in appliance efficiency is driven by two mechanisms: global autonomous improvement towards a theoretical maximum, and regional improvement stimulated by regional energy prices. Increasing electricity price, for example due to carbon tax, stimulates efficiency improvement, hence, a decrease in household electricity consumption. Subsequently, the investments in different end-use technologies (and fuel types) to fulfil demand depend on their relative costs (although some services like lighting and appliances can only be fulfilled by electricity).

Part of the household demand model is the electrification sub model. This model, discussed in detail in Dagnachew et al. (2017), is integrated within the TIMER model, to allow analysis of trade-offs and synergies between electricity access and climate change mitigation (Fig. 1). The model is designed to assess future developments in household electricity access and the role of different technologies. The model determines the least-cost electrification technology (grid-based, mini-grid or stand-alone) per grid-cell, based on the lifetime cost of generation, transmission and distribution of each technology and the consumption density (kWh per km^2 area) of the respective grid-cell, under various policy assumptions (see Section 2 in the supplementary text). The model also calculates the associated investment requirements. The model operates at a $0.5^\circ \times 0.5^\circ$ grid-cell basis and takes key characteristics of the electricity sector into account. Off-grid electrification technologies include mini-grids based on diesel generators, mini-hydro, solar, wind (the last two potentially in combination with a diesel generator), and stand-alone systems based on solar power or diesel generators. The model uses exogenous data on population density (Bright et al., 2013), distance from existing high-voltage power lines (Open Street Maps, 2015) and endogenous data on resource availability (Hoogwijk, 2004), regional electricity prices, and the costs of individual electrification technologies for central grid, mini grid and stand-alone systems.

2.2. Scenario descriptions

Four scenarios are used in this paper to assess the impact of climate mitigation policy on achieving the universal access target, and vice versa: a baseline scenario (BL), a universal electricity access scenario without climate policy (UA), a universal access scenario with global climate mitigation policy imposed in all regions (UA-CP), and a universal access scenario with global climate mitigation policy where Sub-Saharan Africa is exempted from carbon price (UA-NCP). Table 1 provides a short description of these four scenarios.

The scenarios are all based on the exogenous assumptions and

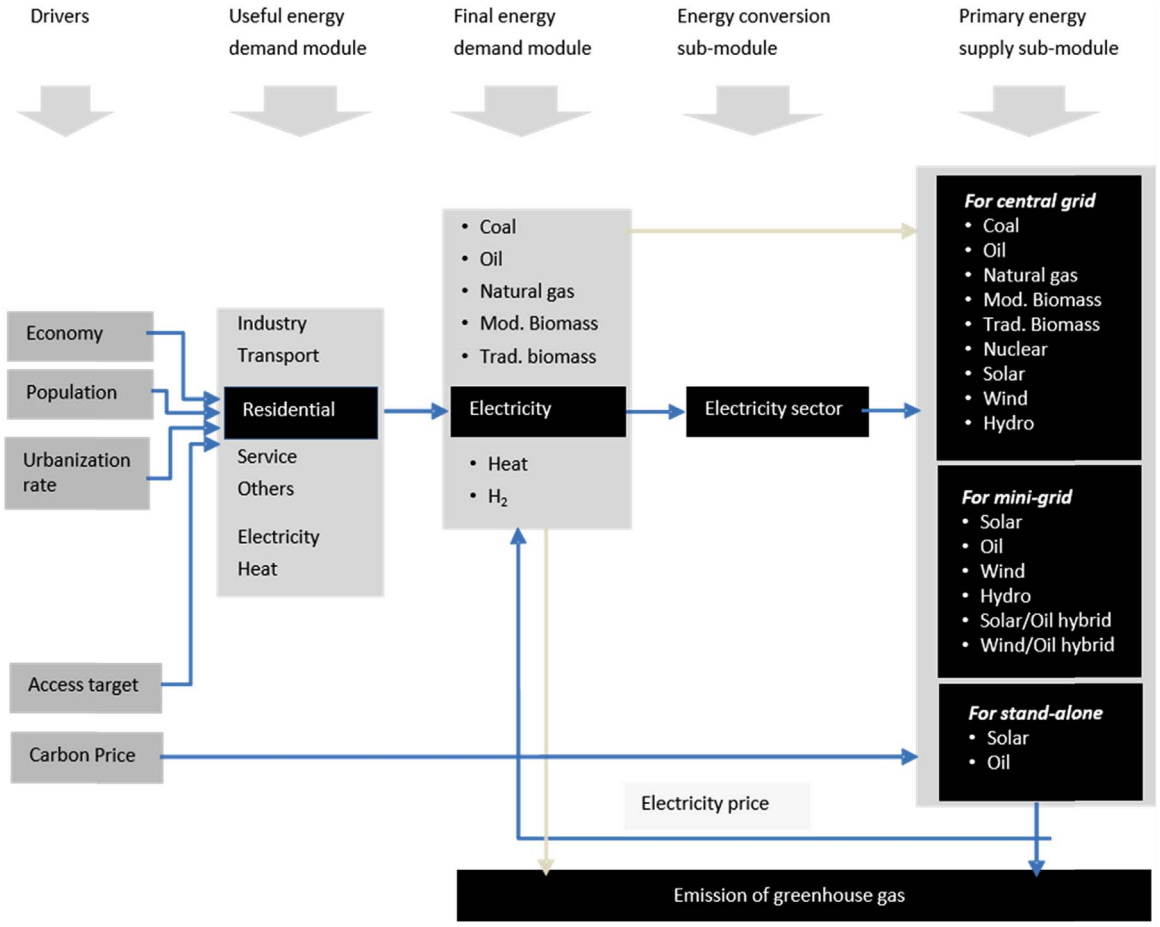

Fig. 1. The Sub-Saharan Africa electrification model integrated in the TIMER Model (modified from (van Vuuren et al., 2006a).

projections of the drivers of energy demand (e.g. population growth, economic development, rate of technology change, and rates) of the Shared Socioeconomic Pathways (SSPs), as implemented in IMAGE (Van Vuuren et al., 2017a). The SSPs provide narrative descriptions and quantifications of possible developments of socio-economic variables that characterize challenges to mitigation and to adaptation (O'neill et al., 2013, 2015). Here we use the IMAGE implementation of the SSP2 scenario because it represents a ´middle-of-the-road scenario´ regarding population and economic growth (Table 2). As household electricity access and demand is strongly dependent on these variables, it can also be viewed as 'middle-of-the-road' regarding baseline access rates and demand levels. Both technology development and social acceptance for all energy conversion technologies are assumed to be 'middle-of-the-road'. In SSP2, the Sub-Saharan Africa population is expected to grow from 860 million in 2010 to over 1.3 billion in 2030, with the economy almost doubling during this period (see Kc and Lutz, 2017, Dellink et al., 2017). Table 2 shows the socio-economic drivers in 2010 and in 2030, under the SSP2 scenario (Section 4 of the Supplementary material provides a comparison of these drivers with other SSPs).

In the BL scenario, electrification rates are determined endogenously to the model, based on GDP per capita, population density, and urbanization rate. In the three UA scenarios, full electricity access in Sub-Saharan Africa by 2030 is imposed exogenously to the model. In the UA scenarios, access to electricity increases from the regions' 2010 levels, to 100% in 2030. In the UA-CP scenario, a global mitigation policy in the form of a price on carbon emissions is applied. The carbon price trajectory is taken from the IMAGE implementation of the SSP2-2.6 scenario, and amounts to 43 USD/tCO_2 in 2020, increasing to 110 USD/tCO_2 in 2030 (Van Vuuren et al., 2017b). The carbon price increases the preference for renewable energy carriers and induces energy efficiency measures, and should therefore be interpreted as a universal stimulus for cost-effective climate polices. In practice, a similar strategy can be targeted through other policy measures, such as specific energy efficiency policies. Such policies can have different effects on energy access and these effects are not assessed in this paper. In the UA-NCP scenario, the same carbon price trajectory as in the UA-CP scenario is used, but Sub-Saharan Africa is exempted from the global carbon price. This scenario is added to test how sensitive the results are to developed countries taking the lead in international climate policy. It also allows exploring the extent to which external climate policy would indirectly impact electrification decisions in Sub-Saharan Africa.

3. Results

This section presents the results on key indicators that describe the demand, production, and costs of the electricity system, as summarized in Table 3. We describe the results in more detail in Sections 3.1, 3.2 and 3.3.

3.1. Electricity demand

3.1.1. Electricity access

Based on the assumed continuation of the historic correlation between electricity access and GDP per capita, population density, and urbanization rate in the model (Daioglou et al., 2012), the BL scenario shows a considerable increase in the percentage of the population with access to electricity. In total, more than 550 million people are projected to have gained access in Sub-Saharan Africa by 2030. However, this leaves about 515 million people without access to electricity. Eastern Africa will have the highest proportion of people without access

Table 1
Scenario names and descriptions.

Scenario name	*Abbreviation*	*Description*	*Model implementation*		*Objective*
			Access rate	*Carbon price*	
Baseline	BL	- A business-as-usual path - No measures are taken to increase electricity or improve supply	- Endogenous - Varies by region	- None	To explore and explain how the electricity sector would evolve without additional policies and interventions
Universal access	UA	- Universal access for all households based on a least-cost option	- Exogenous - 100%	- None	To understand the impact of providing universal electricity access by 2030 on the electricity sector
Universal access with mitigation policy for all	UA-CP	- Universal access for all households based on a least-cost option - Stringent global climate mitigation policy in all regions, including Sub-Saharan Africa	- Exogenous - 100%	- 43USD/tCO2 in 2020, increases to 110USD/tCO2 in 2030 - All regions	To explore the impact of global climate mitigation policies on the electricity sector and eventually on the universal access target
Universal access with mitigation policy for all but Sub-Saharan Africa	UA-NCP	- Universal access for all households based on a least-cost option - Stringent global climate mitigation policy in all regions except Sub-Saharan Africa	- Exogenous - 100%	- 43USD/tCO2 in 2020, increases to 110USD/tCO2 in 2030 - Sub-Saharan Africa is exempted	To investigate the impact of imposing climate policy in the rest of the world on achieving universal access in Sub-Saharan Africa

to electricity by 2030, followed by the rest of southern Africa, western and central Africa, and the Republic of South Africa.

3.1.2. Household electricity consumption

The average annual household electricity consumption in 2010 was under 350 kWh in all Sub-Saharan regions, except for the Republic of South Africa. The projected annual growth in electricity consumption between 2010 and 2030 ranges from 2% per year in the Republic of South Africa, to 6% in eastern Africa. Fig. 3 shows the resulting projected average levels of electricity consumption (of those households that have access to electricity) for urban and rural households in 2010 (left), and in 2030 (right), for the five income quintiles under baseline assumptions. In the UA scenario, the same level of household electricity consumption as in the BL scenario is assumed – but with more households having access. The introduction of climate mitigation policy leads to significant efficiency improvements in consumption, resulting in a total electricity saving of around 20% by 2030 in the UA-CP scenario, relative to the UA scenario (Table 3). Fig. 2 demonstrates the electricity consumption per capita under UA and UA-CP scenarios. In all the scenarios, the appliance ownership per household is the same. Thus, the decrease in electricity consumption under UA-CP scenario implies a notable improvement in appliance efficiency attributed to the purchase of efficient appliances and the efficient use of the appliances. Under the UA-NCP scenario, where Sub-Saharan Africa is exempted from the carbon price, no significant efficiency improvements are projected.

The World Bank multi-tier framework has been introduced to communicate different levels of ambition with regard to electricity access, including household consumption levels (ESMAP, 2015). Thus, it provides a useful comparison to our projected consumption levels. The multi-tier framework distinguishes electricity consumption levels ranging from very low (Tier 1, i.e. $\geq$ 4.5 kWh; which allows the use of very low-power appliances such as light bulbs and phone charging), to medium (Tier 3 $\geq$ 365 kWh, which allows the use of low-power appliances such as TV, fan and low-power refrigeration), to very high (Tier 5 $\geq$3000 kWh, which allows the use of high-power appliances such as refrigerators and air conditioners). Average electricity consumption levels are projected to be around Tier-3 in eastern Africa by 2030, while in western & central Africa, and in the rest of southern Africa, it reaches levels halfway between Tier-3 and Tier-4 (with large differences in household electricity consumption between income groups). The Republic of South Africa has the highest projected consumption levels, with around Tier-5 in urban areas and between Tier-4 and Tier-5 in rural areas. The large differences between regions can be illustrated by the projection that the highest income group in eastern Africa consumes less electricity than the lowest income group in the Republic of South Africa. Earlier studies used household consumption levels of 250 kWh and 500 kWh per household per year for new connections in rural and urban areas, respectively, in their analyses, which is in between Tier-2 and Tier-3 (Szabo et al., 2011; IEA, 2014).

3.1.3. Total residential electricity demand

Stark population growth, significant increase in electricity access and increasing levels of household electricity consumption push up total residential electricity demand in the region. Even without achieving the universal access target, total residential electricity demand in the BL scenario is projected to increase from 90 TWh in 2010 to almost 270 TWh in 2030 (Table 3). This implies an average annual growth rate of nearly 6% between 2010 and 2030. In the UA scenario, electricity demand reaches 330 TWh (Table 3). This is 23% more than in the BL scenario, raising the annual growth in electricity demand to 7%.

While the rural population is projected to account for 52% of the total population in 2030, in the BL scenario it represents 85% of the population without access to electricity. In this context, it is important to reiterate that household electricity demand in rural Sub-Saharan Africa is much lower than in urban areas under all scenarios. As a

Table 2
Socio-economic data under SSP2 scenario (Dellink et al., 2017; Kc and Lutz, 2017; Jiang and O'neill, 2017).

Region	Population (million)		GDP per capita (USD/cap)		Urban population (%)	
	2010	2030	2010	2030	2010	2030
World	6920	8323	9891	17,389	51%	60%
Sub-Saharan Africa	864	1329	1979	3721	37%	48%
Western & central Africa	417	656	1586	3400	44%	55%
Eastern Africa	260	403	1228	2406	24%	33%
Republic of South Africa	50	59	9252	16,407	62%	72%
The rest of southern Africa	137	211	1943	3682	35%	46%

consequence, the associated increase in electricity demand in urban areas still accounts for 40% of the total.

The efficiency improvements resulting from global climate policy almost completely offset the additional electricity generation needed for achieving universal access in the UA scenario. The electricity demand for the additional connections under UA-CP is projected to be 21 TWh less than what is projected under the UA scenario, while providing the same energy services.

3.2. Electricity production

The electricity mix and related CO_2 emissions largely depend on the electricity system (on-grid, mini-grid or stand-alone) and the prices of different energy carriers.

3.2.1. Least-cost electrification system

Sub-Saharan Africa is characterized by a large number of sparsely populated rural settlements, where many households have a very low income and hence low levels of electricity consumption. Under these circumstances, off-grid systems - including mini-grids and stand-alone systems - could play a vital role in providing electricity access at reasonable cost. However, extending the transmission and distribution infrastructure to cities and communities, for which on-grid electrification is cost-effective, also brings the grid closer to relatively remote communities, thereby increasing the cost-effectiveness of grid connection compared to off-grid systems. Therefore, the timing of electrification of a grid-cell affects the choice of the technology: every time a grid-cell gets access through the main power line, another grid-cell gets closer to the central grid. Targeting universal access changes the dynamics of the electrification process, due to the increasing number of people that will get access every year, and the higher rate of learning of new technologies.

Out of the 550 million people gaining access by 2030 in the BL scenario, only 16% (95 million people) gain access through off-grid systems. An important reason is that, according to the model projections, 90% of the Sub-Saharan Africa population is concentrated on just 45% of the region's land area. This, together with the growing electricity demand, largely favours the central grid. Moreover, most of the people gaining access under BL scenario live in urban areas.

In the UA scenario, off-grid electrification systems are projected to be the least-cost option for close to 7% of the additional connections, i.e. nearly 15 million people, bringing the total number of people connected to off-grid systems to 110 million (Table 4 and Fig. 4). In parts of eastern Africa (South Ethiopia, Somalia, South Sudan and Madagascar) and central Africa (Chad, Central African Republic and Democratic Republic of Congo), people live relatively dispersed and household electricity demand is much lower than in the other regions, favouring off-grid systems.

Climate policy stimulates expansion of renewable energy-based off-grid systems, as a consequence of both higher fossil fuel prices and decreasing consumption levels due to considerable efficiency improvements (see Fig. 2). Therefore, 10 million more people are connected via off-grid systems in the UA-CP scenario than under UA scenario. In the UA-NCP scenario, climate policy outside of Sub-Saharan Africa could influence the African electricity system through inducing faster learning of low-carbon technologies and through lower fossil fuel prices (as a result of reduced demand in other regions as a consequence of climate policy). Our results show the first effect to be slightly stronger than the second one, and therefore there are slightly more people (2 million) connected by off-grid systems in the UA-NCP scenario than in the UA scenario. In all scenarios, the majority of the people connected through off-grid systems live in eastern Africa (almost 60%) and western & central Africa (30%) (Table 4).

The production from stand-alone diesel generators is projected to be 70% lower in the UA-NCP scenario than in the UA scenario (Fig. 5). At the same time, the UA-NCP scenario includes more solar mini-grids, solar home systems, and diesel mini-grids. Urban areas show an increase of mainly solar mini-grids, while in rural areas solar mini-grids, diesel mini-grids and solar home systems all increase. In the UA-NCP scenario, climate policy induces barely any additional efficiency improvements in Sub-Saharan Africa. In this scenario, the renewable energy developments in other regions lead to a slight increase in the share of PV mini-grids in all regions (and a slight decline in central generation). Wind power and PV-diesel hybrid plants become increasingly competitive with diesel mini-grids, but are still projected to be the least-cost options for as few as approximately 100 thousand people in eastern Africa. The share of diesel stand-alone systems is much higher than under the UA-CP scenario, but slightly lower than under the UA scenario.

3.2.2. Electricity mix

The electricity mix is largely determined by the relative costs of different technologies. Costs of renewable power generation

Table 3
Matrix showing the results of our analysis under different scenarios in 2030.

Scenarios	*Demand*		*Production*		*Costs*	
	Population with access to electricity (%)	*Total residential electricity demand (TWh)*	*Share of low-carbon technologies in the electricity mix (%)*[a]	*CO_2 emission from residential electricity use(Mt)*	*Average electricity prices (USD/MWh)*[b]	*Cumulative 2010–2030 investments in production, transmission and distribution (billion USD)*
BL	63	266	46	31	55.4	313
UA	100	330	45	39	56.3	970
UA-CP	100	270	67	13	85.8	840
UA-NCP	100	330	45	39	56.1	976

[a] Shows the average share of all four regions.
[b] Shows the average electricity price of the four regions.

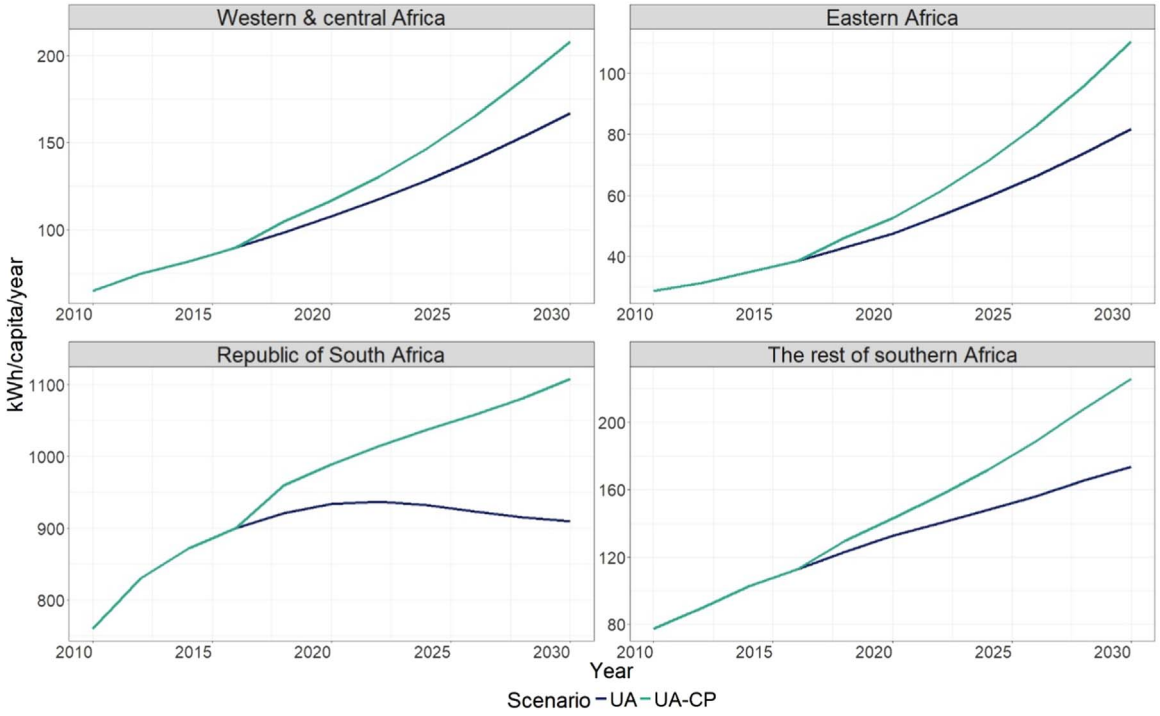

Fig. 2. Electricity consumption per capita per year under UA and UA-CP scenarios.

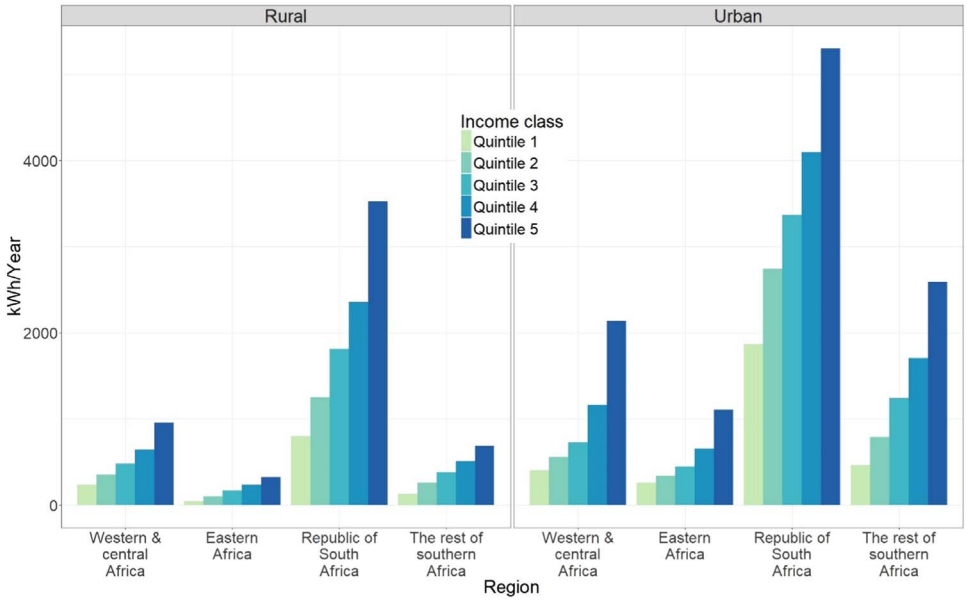

Fig. 3. Rural and urban annual household electricity demand projections for 2030 under the SSP2 scenario.

Table 4
Total number of population (in millions) connected with on-grid and off-grid system under BL, UA, VP and NACP scenarios in 2030.

Scenario variant	*Western & central Africa*		*Eastern Africa*		*Republic of South Africa*		*Rest of southern Africa*		*Sub-Saharan Africa*	
	On-grid	Off-grid	On-grid	Off-grid	On-grid	Off-grid	On-grid	Off-grid	On-grid	Off-grid
BL	428	27	150	57	52	0	107	10	737	94
UA	622	33	336	66	59	0	200	10	1217	109
UA-CP	619	36	333	69	58	1	198	12	1208	118
UA-NCP	622	33	336	66	59	0	198	12	1215	111

technologies, particularly solar and wind, have decreased significantly over the last decades, largely driven by innovation in technology and policy (IRENA, 2017). The model projections show a continuation of this trend, with solar and wind in particular becoming increasingly competitive with fossil fuels over the coming decades. The cost of wind energy is low, especially in eastern Africa, where the largest single wind

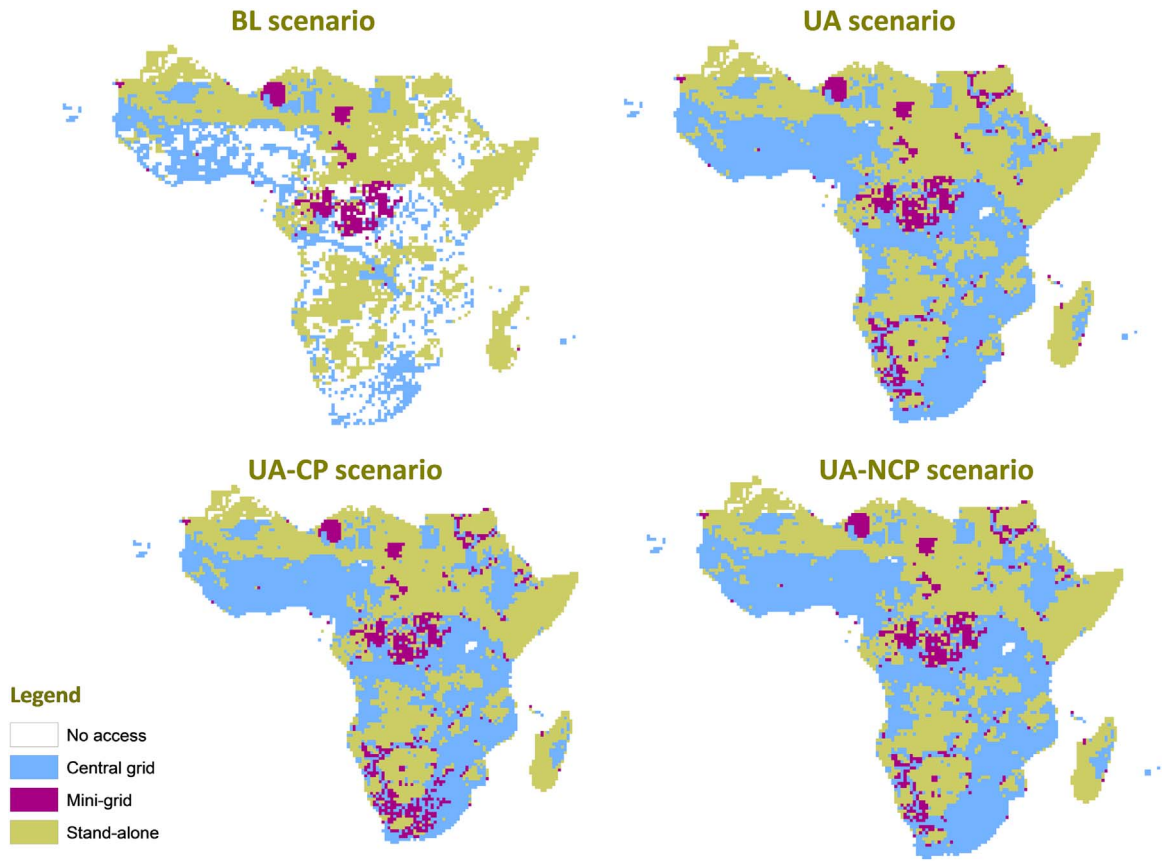

Fig. 4. Least-cost electrification systems under BL, UA, UA-CP and UA-NCP scenarios.

power project in Africa, the Lake Turkana Wind Power project, is being built. Hydropower and coal-based electricity production remain cheap, while prices of oil and gas-based electricity production are projected to increase over time (Fig. 6).

In the UA scenario, additional on-grid generation capacity is mostly the scaling-up of existing capacity (see Fig. 7). For western & central Africa, this is primarily based on natural gas and hydropower, reflecting the abundance of these resources. In eastern Africa over 65% of the additional capacity is projected to come from renewable energy sources, with hydropower being by far the largest electricity source by 2030, which is especially due to high shares of hydropower in Ethiopia, Tanzania, Kenya and Uganda. Natural gas (driven by recent discoveries in Tanzania) and geothermal (particularly in Ethiopia and Kenya) are also projected to play significant roles in the region. The Republic of South Africa continues to rely primarily on coal. Finally, the rest of southern Africa is projected to rely mainly on coal and hydropower in 2030. As a result, the share of renewable energy in the total electricity mix is projected to decrease in all regions except the Republic of South Africa by 4–6%-points (see Fig. 7). Only in the Republic of South Africa is there little change in the electricity mix, as the projected extra electricity demand is relatively low, and the energy mix is already dominated by coal.

In the UA_CP scenario, the changes in electricity mix resulting from global climate policy varies between the regions. Coal is projected to decrease significantly in the energy mix in all regions. Furthermore, while total electricity production from renewable energy sources does not change much in absolute terms, its share increases. The share of natural gas as a fuel for combined-cycle power plants also increases, as i) its carbon content is lower than coal and ii) it can be efficiently used for balancing fluctuating renewable resources. The model also projects

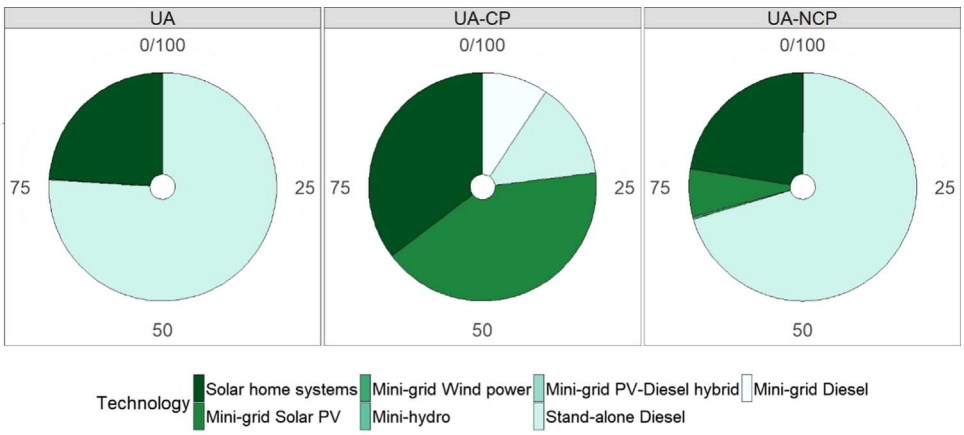

Fig. 5. Sources of electricity for off-grid systems for the additional connections in %MWh by source.

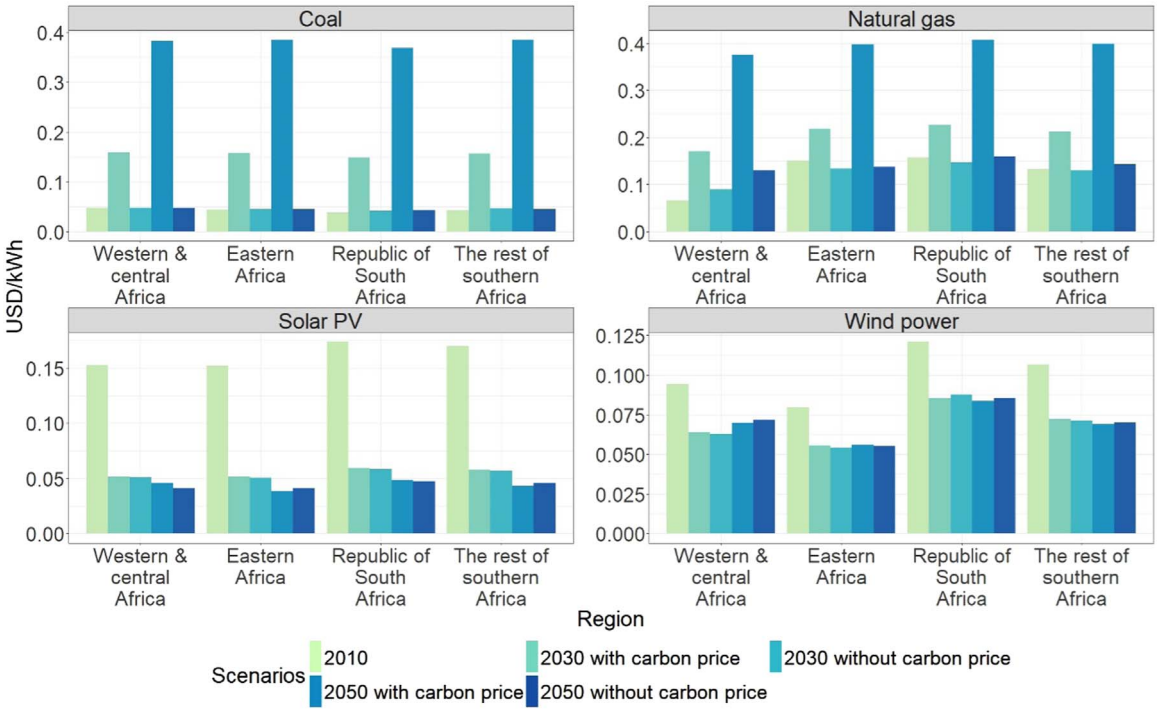

Fig. 6. LCOE of electricity generation from selected energy carriers.

a significant increase in nuclear energy, especially in the Republic of South Africa. Several countries in Sub-Saharan Africa have considerable uranium reserves and the Republic of South Africa has two nuclear power plants currently providing approximately 5% of its total electricity use. Overall, the global carbon price pushes Sub-Saharan Africa onto a renewable energy pathway. In eastern Africa, where the renewable energy share is already high, it is projected to reach almost 100% in 2030, from 58% in 2010. In the Republic of South Africa, the share of low-carbon fuel is also projected to increase significantly, reaching 45% in 2030 (including nuclear), starting from 6% in 2010. Carbon Capture and Storage (CCS) also plays a role in reducing emissions from coal-fired, natural gas-fired and biomass power plants. In western & central Africa, and in the rest of southern Africa, the global carbon price offsets the projected decline in the renewable energy share in the UA scenario, when no global carbon price is applied.

Under the UA-NCP scenario, the electricity mix changes only slightly relative to the UA scenario. In western & central Africa, the share of coal, solar PV and wind decline marginally (0.5%, 1.3% and

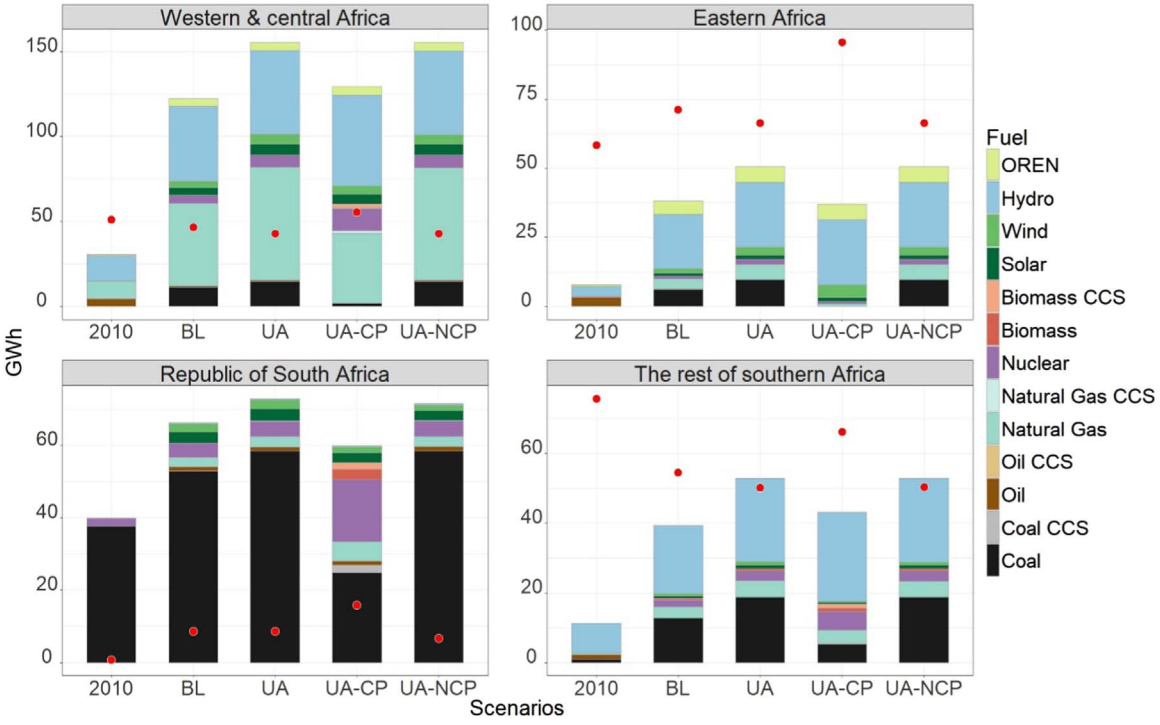

Fig. 7. Total generation mix for the residential electricity demand (the red dots show the share of renewable energy in the mix).

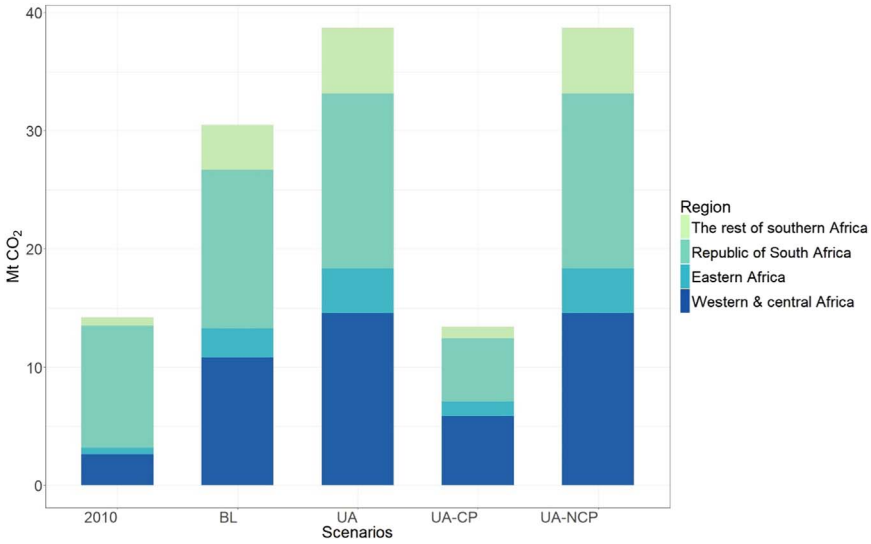

Fig. 8. Electricity related CO_2 emissions from the residential sector in Sub-Saharan Africa under BL, UA, UA-CP and UA-NCP scenarios.

1.7%, respectively), while the share biomass increase by 14%. The electricity mix in eastern Africa remain more or less similar to the UA scenario except for a marginal decline in the share of solar PV (1.2%) and wind (1.6%), which is compensated by an increase in hydro power. In the Republic of South Africa solar PV (15%) and wind power capacity (40%) show a decline, while oil and natural gas increase by 1% and 2.5%, respectively. A slight decline in natural gas-fired plants (2%), solar PV (1%) and wind power capacity (2.5%) in the rest of southern Africa is balanced by a marginal increase in production from nuclear (1%) and hydro power plants (1%).

3.2.3. CO_2 emissions

In 2010, residential CO_2 emissions from electricity accounted for around 25% of total electricity-related CO_2 emissions in Sub-Saharan Africa and only around 0.5% of global electricity-related CO_2 emissions, of which two-thirds is from the Republic of South Africa. Driven by the rapid increase in residential electricity demand, total residential electricity-related CO_2 emissions in the BL scenario are projected to increase from 14 Mt in 2010, to 31 Mt in 2030, which amounts to an increase of 4% per year (Fig. 8). Despite this relatively large increase, the share of Sub-Saharan Africa in global electricity-related emissions is projected to remain very small: 0.7% in 2030. As a consequence of the fuel switch and the use of more efficient coal and gas-powered power plants, the carbon intensity of the central grid is projected to decrease in western & central Africa, and in the Republic of South Africa, somewhat mitigating the increase of CO_2 emissions. In the rest of southern Africa, a growing use of coal increases the carbon intensity in the region.

Achieving the universal access target will inevitably result in an increase in electricity-related residential emissions. Indeed, the projections show that providing electricity access to an additional 500 million people results in an emissions increase of 8 Mt CO_2, i.e. 27% on top of the 2030 value in the BL scenario. This increase is negligible, as it is only around 0.2% of the global electricity-related emissions. Besides, access to electricity could also provide climate benefits that are not accounted for in our study. For example, switching from kerosene to electric lighting could reduce related climate forcing with a factor 10, due to the avoided black carbon emission (Alstone et al., 2015).

Under the UA-CP scenario, the shift to low-carbon energy sources and efficiency improvements results in a total CO_2 emissions reduction of 65% in 2030, relative to the UA scenario, bringing total residential emissions from electricity to below 2010 levels. This scenario shows that emissions peak around 2020, followed by a rapid decline. Under UA-NCP scenario, on the other hand, electricity-related emissions from the residential sector are almost the same as under the UA scenario. The slight increase in the share of renewable technologies in western & central Africa and in the rest of southern Africa, together with some efficiency improvements in power generation and transportation, result in only a marginal decrease in electricity-related CO_2 emissions from the residential sector.

3.3. Electricity prices and investments

3.3.1. Electricity prices

Climate mitigation policies are projected to result in higher electricity prices in all regions, with higher increases in regions with large shares of fossil fuels in their electricity mix (Fig. 9). Eastern Africa has the highest share of low-carbon electricity generation and, therefore, the carbon price leads to the lowest electricity price increase of the four regions (25% by 2030, compared to the UA scenario). In the rest of southern Africa, mitigation policies will increase the price by nearly 40%, due to a strong dependency on natural gas (which is the primary

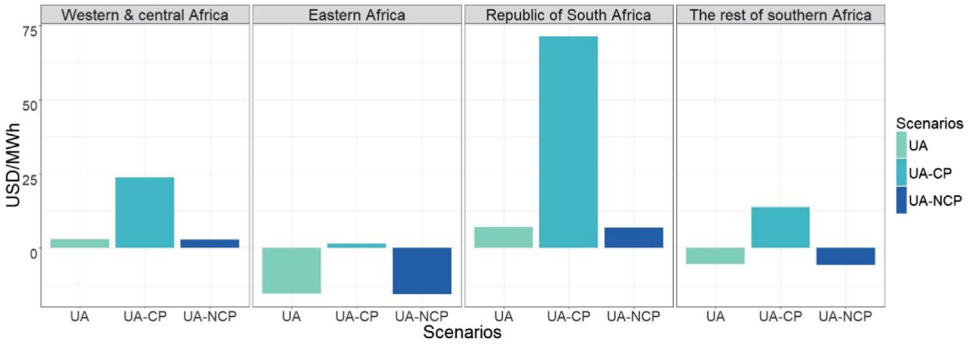

Fig. 9. Projected change in electricity prices under UA, UA-CP, and UA-NCP scenarios in 2030 relative to 2010.

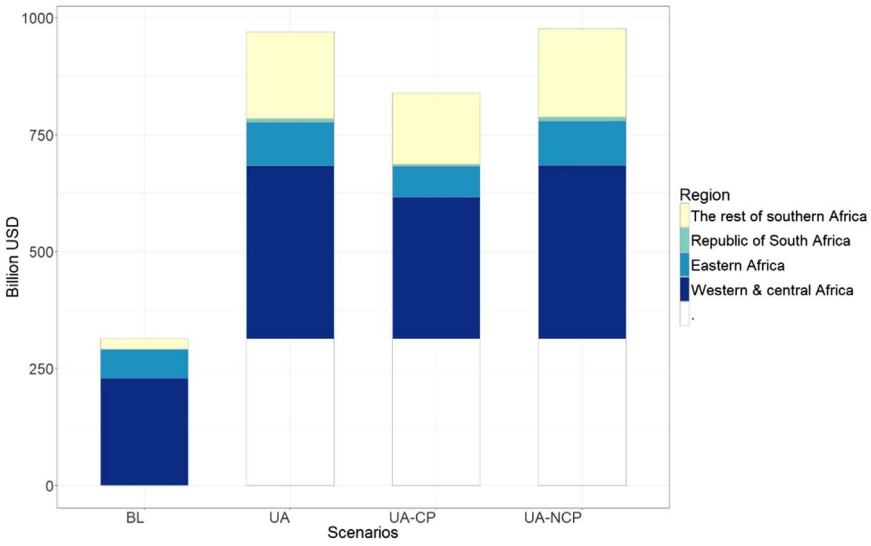

Fig. 10. 2010–2030 cumulative investments for electricity access in various scenarios.

source of electricity, particularly in Angola, Mozambique and Tanzania). In western & central Africa, the carbon price is projected to increase the electricity price by 35% in 2030, relative to the UA projection. This again reflects the dominance of fossil fuel in the electricity mix, which is affected by carbon price. The Republic of South Africa is most affected by the carbon price, due to the strong dominance of coal in its electricity mix. In the UA-CP scenario, the projected electricity price shows an annual average increase of 5% between 2010 and 2030, leading to an electricity price in 2030 that is more than twice the level of the price without a carbon price. The UA-NCP scenario has almost identical electricity prices to the UA scenario, showing that the carbon price in the rest of the world has a negligible effect on electricity prices in Sub-Saharan Africa.

3.3.2. *Electrification investments*

The projected expansion in installed capacity and transmission and distribution infrastructure in all scenarios require large investments. Under the BL scenario, the total cumulative investment of 2010–2030 is projected to be around USD 310 billion, equivalent to an average of USD 16 billion per year (Fig. 10). This is approximately twice the current level of annual infrastructure investment (Brahmbhatt et al., 2016). The increase is mostly a result of the anticipated growth in electricity demand during this period. Recurring costs, such as for fuels and operation and maintenance, are projected to average USD 5 billion per year. The highest investment requirements by far are for western & central Africa, where 55% of the newly connected population lives. The region requires investments for the refurbishment of existing power plants, significant capacity addition to meet the growing electricity demand, and an extension of the transmission and distribution infrastructure for more than 50% of the newly connected population. In contrast, total investment requirements in the Republic of South Africa are relatively low. The country already owns an extensive high-power grid with a large share of the population already connected; hence, the projected investments are mostly for expansion of generation capacity.

Achieving the universal access target will require significant further expansion of installed capacity, as well as transmission and distribution infrastructure. In the UA scenario, to provide electricity access to the additional population, a projected cumulative investment of USD 660 billion, or USD 33 billion per year, is required between 2010 and 2030, on top of the projected investments in the BL scenario. These investment requirements include expanding generation capacity and extending transmission and distribution infrastructure. They do not include funding requirements for capacity development, such as research and development, planning, and policies and regulations, which could also be significant. The bulk of this investment (85%) goes to upgrading and extending the transmission and distribution infrastructure, reflecting the severe lack of transmission and distribution networks and inefficiency of the system. A study by IEA (2014) also confirms the need for large investment in the transmission and distribution system. More than half of the additionally connected population in western & central Africa require an extension of high and medium voltage transmission and distribution infrastructure, which is associated with large investment costs. In eastern Africa, around 20% of the additional connected population requires an extension of the high and medium voltage transmission and distribution infrastructure.

In the UA-CP scenario, the additional investment requirement for generation capacity and transmission and distribution infrastructure by the additional connected population is projected to be around USD 27 billion per year (Fig. 10). This is 20% less than what is required under UA scenario, which can be explained by the efficiency improvements in household appliances and electricity production (see Section 3.1.2) The UA-NCP scenario requires almost the same level of investment as in the UA scenario, since household consumption, generation, and transmission and distribution systems are largely similar. The marginal increase in cumulative investment is the result of the shift from diesel generators to wind and solar mini-grids, and solar home systems, which have higher initial investment costs (but lower running costs). These investment requirements do not include the costs of climate change mitigation policies that will add to the investment requirements of the UA-CP scenario.

4. Discussion

Our results are reflections of the model dynamics, the data input and the scenario designs. We acknowledge that there are large uncertainties in our model projections. Different socio-economic projections (population size, population density, household size, income) might result in different magnitudes of emissions, investments, or different energy mixes. The same is true about network design, learning rates of new technologies, fuel prices, technological deployment, price elasticity, etc. Moreover, the model results are a simplification of the real-world situation.

The model uses high-resolution data on a $0.5^{\circ} \times 0.5^{\circ}$ grid-cell for population size, population density, renewable energy potentials and renewable energy prices. This allows a more detailed representation of demand density, energy resource potentials and technology prices than when only regional dynamics are considered The model chooses from a number of electrification technologies, which, in addition to the central

grid, include mini-grids based on diesel, hydro, solar, and wind (eventually in combination with diesel); and stand-alone systems, based on solar and diesel. Data on diesel prices, electricity prices, household size, household electricity consumption and generation mix are more aggregated at regional levels. This means that we miss important local differences. For example, diesel prices vary significantly between oil producing countries and oil importing countries, while in our model they are grouped within the same region.

Due to data restrictions, we assume that everyone that has access to electricity in 2010 is connected to the central grid. If the share of existing off-grid connections is considerable, it might lead to different dynamics in the electricity system. Furthermore, we have not addressed the roughness of the terrain in selecting the electrification system or technology. Similarly, differing costs for transmission and distribution networks can be found in the literature (Deichmann et al., 2010; Nerini et al., 2016). The transmission and distribution costs used in our model are at the lower estimates of the literature. Higher transmission and distribution costs will mostly likely lead to higher shares of off-grid systems.

A comparison of our results to those of other studies shows that our projection of additional annual investment requirements of USD 33 billion to achieve the universal access target is significantly higher than the USD 19 billion estimated by IEA (2011), but within the range of USD 20–50 billion projected by IRENA (2012). Bazilian et al. (2012) estimate that the additional cost of achieving universal electricity access will amount to USD 740 billion between 2011 and 2030, based on an annual average electricity consumption of 1285 kWh per capita in 2030, which is considerably higher than our estimates. This gap can be explained by differences between the models in household electricity consumption, household size, cost of technologies, and shares of off-grid technologies in the electricity system. Our estimates of the number of people without access under baseline developments is similar to the estimate by the IEA (2014); 515 million people by 2030 and 530 million people by 2040, respectively. Similarly, our projections for residential electricity demand show an annual average growth rate of 6% and 7% between 2010 and 2030 under BL and UA scenarios, respectively. This is quite similar to the estimate of 6% between 2010 and 2040 projected by the IEA (2014). The same report also shows an average annual growth rate of household electricity consumption of 2–7%, depending on the region, which is similar to our estimate of 2–6%. The two models also agree that the bulk of the investment requirement goes to expansion of the transmission and distribution system in the region.

The synergy between climate mitigation and universal electricity access are largely the result of projected household appliance efficiency improvements. The projected household appliance efficiency depends on two consumer actions: the purchase of efficient appliances and the efficient use of the appliances. Together with an increase in electricity prices, energy-efficiency improvements result in a huge reduction in household electricity consumption. In reality, other measures promoting energy efficiency, such as appliance energy performance standards and labelling (probably complementing carbon price), might achieve the same result. Besides, we have not addressed the rebound effect of improved appliance efficiency and related market failures.

The analysis of resource requirements for achieving the universal access target in Sub-Saharan Africa are indicative estimates and are by no means precise figures, but are instead intended to indicate the order of magnitude of the efforts and resources that will be needed if the target is to be met. The identified synergies and trade-offs between climate mitigation policies and universal access to electricity in Sub-Saharan Africa are robust to the above-mentioned uncertainties.

5. Conclusions

In this paper, we have used the IMAGE-TIMER integrated assessment model to analyse trade-offs and synergies between climate mitigation policies and achieving universal electricity access in Sub-Saharan Africa. The analysis focused on differences in electricity demand, production, and costs under four different scenarios, focusing on several key indicators. Three of the scenarios target universal access to electricity by 2030: one without specific climate mitigation policy; another with global coordinated climate policy in the form of a carbon price; and a third, with global coordinated climate policy that exempts Sub-Saharan Africa from carbon prices. Our model does not address the spill overs (co-benefits or adverse effects) of climate mitigation policies on other sectors of the regional economy, nor the institutional requirements and the financing of universal electricity access in the region, which is a different topic altogether. From the model results, we draw the following conclusions:

5.1. The increase in CO_2 emissions due to achieving universal electricity access is small compared to global CO_2 emissions

Current electricity-related residential CO_2 emissions in Sub-Saharan Africa are very low, due to low levels of electricity access and low consumption levels. Without climate policies, achieving universal electricity access in Sub-Saharan Africa considerably increases emissions relative to baseline development. However, the increase in emissions from providing universal access to electricity in Sub-Saharan Africa is negligible relative to global emissions, and it barely influences global climate change. Furthermore, climate mitigation policy could offset the projected increase, due to efficiency improvements and a shift to low-carbon energy sources.

5.2. Synergies between climate mitigation policy and universal access to electricity relate to efficiency improvements and declining renewable technology prices

Sub-Saharan Africa could benefit from a globally coordinated climate mitigation policy through efficiency improvements in household appliances and learning in renewable energy technologies, which seem mutually reinforcing. Renewable electricity generation technologies based on off-grid systems are becoming increasingly competitive with fossil fuel based energy systems. In remote, low-density settlements, off-grid systems (mostly stand-alone) in particular play an essential role in reaching the poorest and most isolated populations (also known as the ‘last-mile’ challenge). This provides an opportunity for Sub-Saharan Africa to decarbonize the electricity system, ensure sustainable development, establish energy security, and avoid fossil fuel lock-in in the long term, while at the same time avoiding billions of USD in energy-system investments.

5.3. Achieving universal electricity access in Sub-Saharan Africa requires at least a tripling of the current annual electricity-system investments of 8 billion USD

Our model projections show that the annual cost of providing universal electricity access between now and 2030 in Sub-Saharan Africa ranges from USD 27 billion with climate policies, to USD 33 billion without climate policies. Efficiency improvements in household appliances could lower the investment requirements for achieving universal access (by 20%, in our model). The regions’ energy potential is neither evenly distributed, nor always located close to demand centres; hence the bulk of the investment requirement in all scenarios is projected to go to expansion of the transmission and distribution system. The annual investment of USD 27 to USD 33 is a significant amount, but it probably understates the full costs of universal electricity access in the most electricity-poor region in the world, due to large uncertainties resulting from lack of data and other challenges, such as political will and corruption that are difficult to model. Besides, these investments do not include the cost of climate change mitigation policies which will increase the investment requirements under UA-CP scenario.

5.4. A global carbon price results in increases in electricity prices

Climate mitigation policy, in our study imposed by a global uniform carbon price, is projected to increase the cost of electricity per kWh that will undoubtedly affect the poor. The price increase is especially large in regions with a high share of fossil fuels in their electricity mix. However, according to several studies, currently, the poor pay more for alternative (and mostly polluting) electricity sources, while being hindered from connecting to existing power lines by high connection fees. Moreover, replacing kerosene and candle lighting by electricity improves household health and safety considerably, while at the same time providing higher quality and quantities of light. To facilitate access by the poor, climate mitigation policies can also be combined with complementary policies, such as free basic electricity, low consumption low tariff, cross subsidization, etc., specifically designed to protect the poor from increasing electricity prices.

Acknowledgements

The research presented in this paper was funded by the Dutch Ministry of Foreign Affairs, through its Directorate-General of Trade and International Cooperation. The work also benefitted from the funding of the European Horizon 2020 Research Programme as part of the CD-LINKS project (Linking Climate and Development Policies-Leveraging International Networks and Knowledge Sharing) under grant agreement no 642147.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2017.12.023.

References

Alstone, P., Gershenson, D., Kammen, D.M., 2015. Decentralized energy systems for clean electricity access. Nat. Clim. Change 5, 305–314.
Bazilian, M., Nussbaumer, P., Rogner, H.-H., Brew-Hammond, A., Foster, V., Pachauri, S., Williams, E., Howells, M., Niyongabo, P., Musaba, L., Gallachóir, B.Ó., Radka, M., Kammen, D.M., 2012. Energy access scenarios to 2030 for the power sector in sub-SaharanAfrica. Util. Policy 20, 1–16.
Brahmbhatt, M., Bishop, R., Zhao, X., Lemma, A., Granoff, I., Godfrey, N., Te Velde, D.W., 2016. Africa's New Climate Economy: Economic Transformation and Social and Environmental Change. DC: New Climate Economy and Overseas Development Institute, London and Washington.
Bright, E.A., Rose, A.N., Urban, M.L., 2013. Landscan digital raster data [Online]. Oak Ridge National Laboratory, Oak Ridge, TN. 〈http://www.ornl.gov/landscan/〉.
Cameron, C., Pachauri, S., Rao, N.D., Mccollum, D., Rogelj, J., Riahi, K., 2016. Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. Nat. Energy 1, 15010.
Dagnachew, A.G., Lucas, P.L., Hof, A.F., Gernaat, D.E.H.J., De Boer, H.-S., Van Vuuren, D.P., 2017. The role of decentralized systems in providing universal electricity access in sub-Saharan Africa – a model-based approach. Energy 139, 184–195.
Daioglou, V., Van Ruijven, B.J., Van Vuuren, D.P., 2012. Model projections for household energy use in developing countries. Energy 37, 601–615.
Deichmann, U., Meisner, C., Murray, S., Wheeler, D., 2010. The economics of renewable energy expansion in rural sub-Saharan Africa. Energy Policy 39, 215–227.
Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the shared Socioeconomic pathways. Glob. Environ. Change 42, 200–214.
ESMAP, 2015. Beyond Connections: Energy Access Redefined. The World Bank Group, Washington DC.
Hollberg, P., 2015. Swarm Grids – Innovation in Rural Electrification (Master of Science). KTH School of Industrial Engineering and Management.
Hoogwijk, M., 2004. On the Global and Regional Potential of Renewable Energy Sources (Doctoral thesis). Utrecht University.
IEA, 2011. Energy for All: Financing Access for the Poor. International Energy Agency, Paris, France.
IEA, 2014. Africa Energy Outlook. A Focus on Energy Prospects in Sub-Saharan Africa. World Energy Outlook Special Report. International Energy Agency, Paris, France.
IRENA, 2012. Prospects for the African Power Sector: scenarios and strategies for Africa project. International Renewable Energy, Abu Dhabi.
IRENA, 2015. Renewable Power Generation Costs in 2014. IRENA, Abu Dhabi.
IRENA, 2017. Rethinking Energy: Accelerating the Global Energy Transformation. International Renewable Energy Agency, Abu Dhabi.
Jiang, L., O'neill, B.C., 2017. Global urbanization projections for the shared Socioeconomic pathways. Glob. Environ. Change 42, 193–199.
Kc, S., Lutz, W., 2017. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. Glob. Environ. Change 42, 181–192.
Lucas, P.L., Shukla, P.R., Chen, W., Ruijven, V.A.N., Dhar, B.J., Den Elzen, S., M, G.J., Van Vuuren, D.P., 2013. Implications of the international reduction pledges on long-term energy system changes and costs in China and India. Energy Policy 63, 1032–1041.
Nerini, F.F., Broad, O., Mentis, D., Welsch, M., Bazilian, M., Howells, M., 2016. A cost comparison of technology approaches for improving access to electricity services. Energy 95, 255–265.
O'neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., Van Ruijven, B.J., Van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2015. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Change.
O'neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., Van Vuuren, D.P., 2013. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Change 122, 387–400.
OECD/IEA, 2015. World Energy Outlook 2015. International Energy Agency.
Open Street Maps, 2015. Project power networks [Online].
Pachauri, S., 2014. Household electricity access a trivial contributor to CO_2 emissions growth in India. Nat. Clim. Chanage 4, 4.
Sanchez, T., Tozicka, T., 2013. Energy for all 2030: rural electrification: The role of the public sector and collective action on electricity access for the poor. Practical Action.
Stehfest, E., Van Vuuren, D.P., Kram, T., Bouwman, L., 2014. Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model description and Policy Applications. PBL Netherlands Environmental Assessment Agency, The Hague.
Szabo, S., Bódis, K., Huld, T., Moner-Girona, M., 2011. Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. Environ. Res. Lett. 6, 034002.
UN-OHRLLS, 2014. Role of the private sector in advancing the implementation of the IPoA: Focus on sustainable energy. United Nations.
UN, 2015. Transforming our world: The 2030 agenda for sustainable development. United Nations.
UNFCCC, 2015. FCCC/CP/2015/L.9/Rev.1: Adoption of the Paris Agreement. UNFCCC, Paris, France.
Van Vuuren, D., Van Ruijven, B., Girod, B., Daioglou, V., Edelenbosch, O., Deetman, S., 2014. Energy Supply and Demand. In: Stehfest, E., Van Vuuren, D., Kram, T., Bouwman, L. (Eds.), Integrated Assessment of Global Environmental Change with IMAGE 3.0 - Model Description and Policy Applications. PBL, The Hague.
Van Vuuren, D.P., Nakicenovic, N., Riahi, K., Brew-Hammond, A., Kammen, D., Modi, V., Nilsson, M., Smith, K.R., 2012. An energy vision: the transformation towards sustainability—interconnected challenges and solutions. Curr. Opin. Environ. Sustain. 4, 18–34.
Van Vuuren, D.P., Riahi, K., Calvin, K., Dellink, R., Emmerling, J., Fujimori, S., Kc, S., kriegler, E., O'neill, B., 2017a. The Shared Socio-economic Pathways: Trajectories for human development and global environmental change.
Van Vuuren, D.P., Stehfest, E., Gernaat, D., Doelman, J.C., Van Den Berg, M., Harmsen, M., De Boer, H.-S., Bouwman, A., Daioglou, V., Edelenbosch, O., Girod, B., Kram, T., Lassaletta, L., Lucas, P.L., Van Meijl, H., Muller, C., Van Ruijven, B., Van Der Sluis, S., Tabeau, A., 2017b. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Glob. Environ. Change 42, 237–250.
Van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Doelman, J.C., Van Den Berg, M., Harmsen, M., De Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P.L., Van Meijl, H., Müller, C., Van Ruijven, B.J., Van Der Sluis, S., Tabeau, A., 2016. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Glob. Environ. Change.
Van Vuuren, D.P., Van Ruijven, B., Hoogwijk, M.M., Isaac, M., De Vries, H.J.M., 2006. TIMER 2: model description and application. In: Bouwman, A.F., Kram, T., Goldewijk, K.K. (Eds.), Integrated Modelling of Global Environmental Change: An Overview of IMAGE 2.4. Netherlands Environmental Assessment Agency (MNP), Bilthoven.